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A Computer Program for Stress Test Data Processing

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Exercise stress tests for evaluation of ischemic heart disease and functional performance of the heart have been used with increasing frequency in recent years. This increase is due to several factors. One of which is the need to objectively evaluate evidence of myocardial ischemia for correction by coronary artery saphenous vein bypass grafting. An additional factor is the evidence that stress testing is a reproducible method for functional evaluation of the patient's performance. Many criteria have been proposed for evaluating the electrocardiogram (EKG) taken during and following exercise to determine the presence of ischemic heart disease (2, 3, 5, 6). Common to all of these criteria, however, is the inability to record adequate signals during exercise. In addition, the volume of data collected requires considerable physician time if adequate interpretation is to be achieved.

This paper describes an on-line computer program developed at the Latter-day Saints Hospital for processing of EKG signals before, during and after treadmill stress testing. The development of these programs began with a number of prerequisites. These requirements included: (1) that the data be collected and processed in an on-line, real-time process; (2) that use of the computer did not endanger the patient's safety; (3) that adequate back-up be present in case of computer failure; (4) that the testing procedure is not prolonged; (5) that the number of personnel and abilities of the assistants performing the test would not be increased by the addition of computer analysis; and (6) that computer processed data provide distortion free signals.

Signal noise during exercise test recordings fall into two categories, the first being baseline wander due to impedance changes in the electrode-skin interface, and the second being muscle artifact. Figure 1 is a recording of an EKG taken on a patient at this hospital during a maximum exercise test. Because of the magnitude of the muscle artifact superimposed on this electrocardiogram, interpretation of the tracing is very difficult. In some points it is almost impossible. Since the noise is present regardless of the particular criteria for determination of normal or abnormal stress response, the first step in any analysis must be the development of a system which reduces the magnitude of noise on the signal.

The programs described in this paper have been written in Control Data 3300 basic assembly language to operate under the MEDLAB time-sharing system (1). They are executed entirely on-line, with the signals from the patient being connected directly to a Control Data 3300 computer system. Thus, review of the processed data during each stage of the test is within seconds of the time when the data was sampled. Following completion of the study, the cardiologist has to only review the data for any final editing before requesting a report to be printed.

The program processes three channels of data simultaneously. The investigator may choose any three leads which he feels will contain maximal information for interpretation of ischemic heart disease. These leads are then “patched” into the computer with the first lead being the “monitoring lead”. The importance of this first lead will be discussed later. Time coherent averaging is performed on each of the channels to reduce the random noise superimposed on the signal. These averages are then presented via a graphics terminal to the cardiologist. He accepts or rejects the averages. If accepted they are stored on a magnetic disc by the computer for the final report. The exercise procedure which is followed at this hospital uses the procedure and stages of exercise as

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described by Bruce (5).

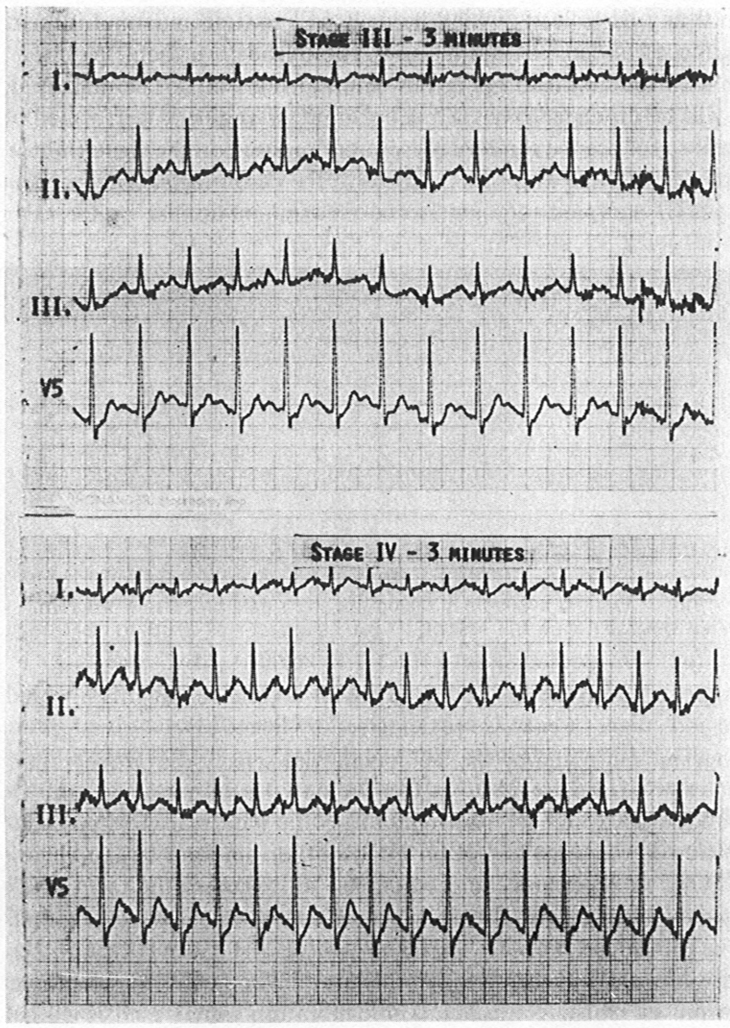

FIG. 1. Typical EKG data as recorded during a stress test.

The program is initiated by the technician who selects the proper option on the computer terminal. Figure 2 shows the computer terminal display of the options available in the program. Option initializes the data storage areas and provides 1 for calibration of the signals. Option 2 causes the computer to sample and process the EKG. Option 3 permits the cardiologist to reprocess the last set of collected data. Option 4 is to review the data processed on the “monitoring lead” at any point in the procedure. To start a test the cardiologist chooses Option 1 and enters the patient’s hospital number through the terminal and calibrates the three channels to be transmitted to the computer. The calibration signal used is a one millivolt signal applied to each of the three channels. Following calibration the cardiologist can process data as often as desired. He does this by choosing the sample option. The computer then samples and processes ten seconds of data (sampled at 200 samples per second) on each of the three channels. This data is stored on magnetic disc. The subsequent processing is from the disc stored data. It is for this reason that the cardiologist can always reprocess the last set of data (Option 3), since it remains on disc until overwritten by the next ten-second sample.

Two basic assumptions are used by the analysis program in order to minimize the processing time and maximize the accuracy. The first assumes that the configuration of the QRS morphology will not change during the test. This implies that the location of the onset and end of the QRS will be constant with respect to a fiducial

FIG. 2. Options available in the on-line *stress* data processing program.

point used in the coherent averaging. This assumption is adequate unless a bundle branch block occurs during the test. The appearance, however, of bundle branch block during a test is an indication for discontinuation of the test. Because of this assumption, the onset and end of the QRS is located by the computer only once during the entire test. They are located on a control lying EKG when the incoming data has a maximum signal-to-noise ratio. The earliest QRS onset and the latest QRS end in the three chosen simultaneous leads are used for the onset and end location. The second assumption is that the data is sampled simultaneously. Because this is in fact true, location of the fiducial point for coherent averaging need be resolved on only one of the leads. The lead chosen for this search is that one with the highest signal-to-noise ratio. This lead is the "monitoring lead" and must be the first lead mentioned above. This not only saves time necessary to search for fiducial points on the other leads, but assures that referencing will be common to all leads and thus there will be no need to search for onset and end of QRS on each lead.

The first step of the program is to locate fiducial points on the QRS (from only the "monitoring lead"). The detection of the QRS complexes is determined by searching the initial 1.5 sec of data for the absolute maximum first difference. The remaining 8.5 sec of data is searched and "flagged" at those locations where the first difference exceeds three-fourths of the maximum difference found during the initial 1.5 sec. Since only normally conducted beats are to be included in the average, it is necessary to discard all premature complexes. Elimination of the premature complexes is accomplished by discarding those complexes where the preceding R-R interval is less than 10% of the median R-R interval for that set. With those QRS complexes that have been accepted for averaging, a search is made over 70 points following the "flagged" point on the QRS. The point

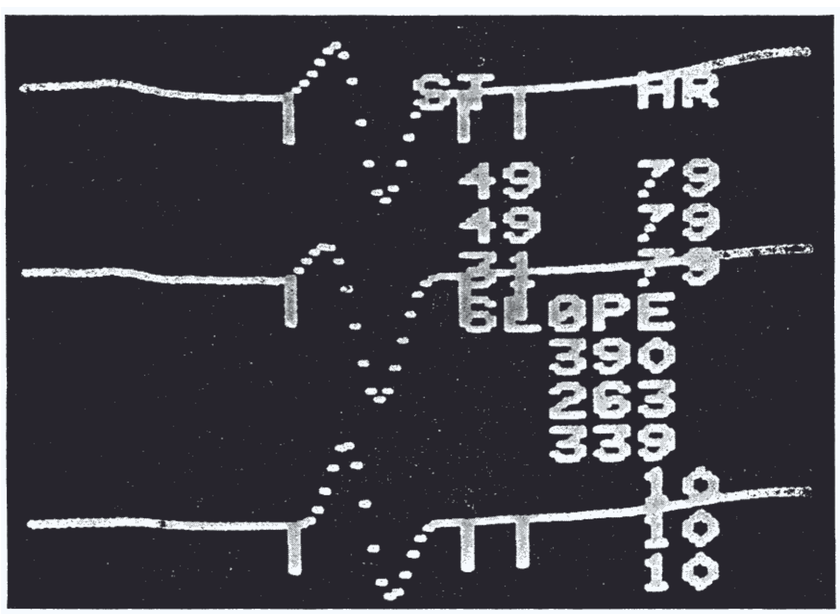

FIG. 3. On-line results of the stress program as seen on the face of the computer terminal.

within this search interval where maximum absolute first difference occurs is the fiducial point about which coherent averaging will take place. The complexes are averaged starting at the fiducial point minus 50 points to the fiducial point plus 49 points. The average will thus contain the entire QRS complex plus sufficient of the *ST-T* wave for analysis of the *ST* segment. If the complex being processed is the initial control "monitoring lead", onset and end of the averaged QRS is located by setting a threshold of 1/8 of the maximum absolute first difference of that complex and searching both backward from the fiducial point for the onset and also forward from that point for the end of the QRS complex. The onset or end is defined as that point where failure of the absolute value of the first difference to exceed the threshold occurs on four successive points. Having thus determined the fiducial point and the start and end of the QRS from the "monitoring lead", the program reads from disc the other two leads to he processed and averages them using the indices (fiducial points, onsets and end of QRS) generated from the "monitoring lead". These three leads are then displayed on the graphics terminal in the laboratory with the small vertical marks indicating the onset and end of QRS. Figure 3 is such a display. As seen in the figure, the following parameters are calculated and displayed at the same time; the heart

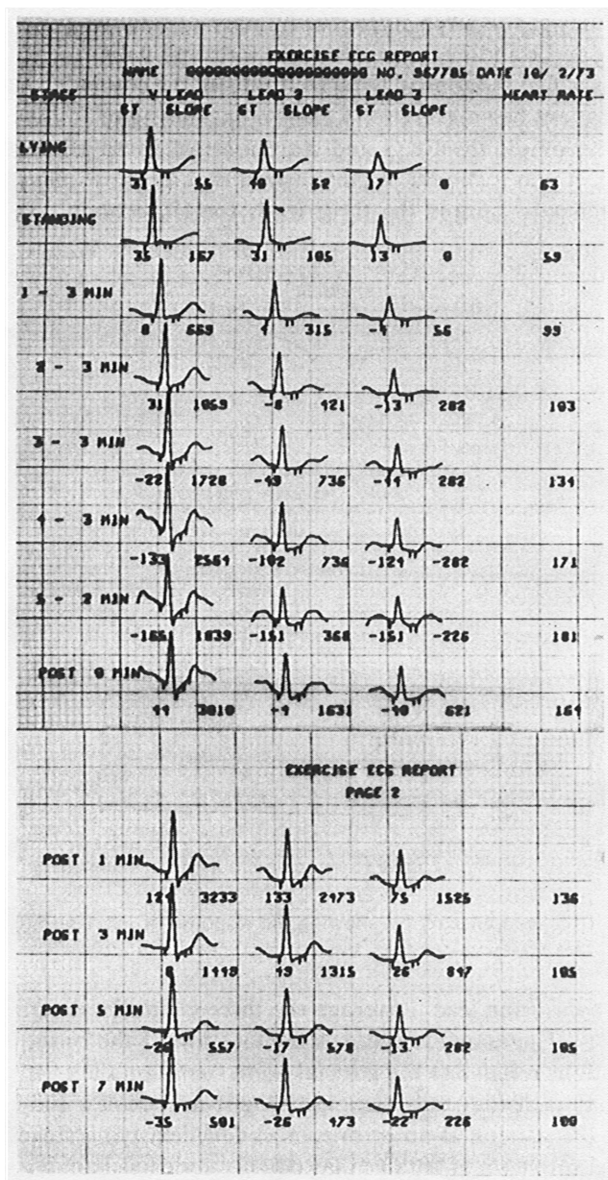

FIG. 4. Par 1 of the computer report of the stress data showing the average complexes and the measured parameter at each stage of exercise.

rate, average *ST* level for each lead and the slope of the *ST* segment for each lead. The numbers in the lower right-hand corner are the number of complexes averaged for that ten-second sample. The *ST* levels are calculated by averaging the eight data points (40 msec) just following the end of the QRS complex. The average slope is the average of the first difference of the eight data points following the end of the QRS.

A manual adjustment of the onset and end of the QRS is available to the cardiologist. This is available, however, only on the initial control analysis. At this time, if the cardiologist feels that the computer location of the onset or end of the QRS is in error he may instruct the computer to move the appropriate mark to the right or left of a given point or data points. Viewing of this initial analysis is thus crucial, since at no other time in the procedure may he modify the computer-determined values. The data is stored in the patient file when an appropriate code from a four-digit thumbwheel switch on the terminal is transmitted to the computer. The first two digits of this code indicate the patient status with 00 for resting; 01 to 06 for exercise stages 1-6 and 07 for post exercise. The second two digits indicate the number of minutes at the given stage, the number of minutes post exercise and 01 and 02 for lying and standing, respectively, in a resting patient.

Having once verified the control lying record from the computer, the test proceeds by having the patient begin exercise. At any point during or following exercise the cardiologist may sample the EKG and store a set of averaged waveforms on the patient's record. Again it should be emphasized that all subsequent processing will cause the computer to sample the three leads for 10 seconds, locate the fiducial point on the "monitoring

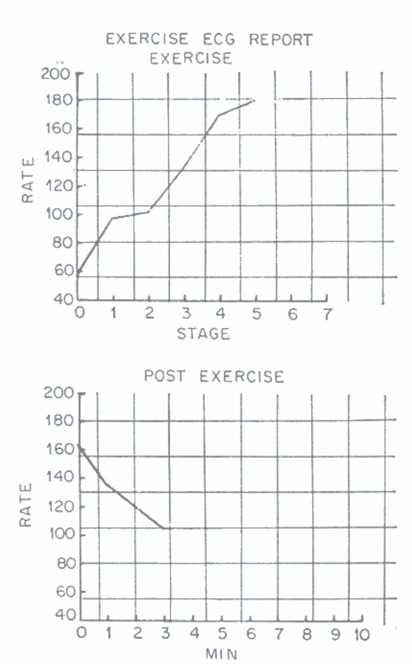

FIG. 5. Part 2 of the computer report showing the response of heart rate to exercise and the post exercise heart rate response.

lead", average the three channels, determine heart rate, and calculate the *ST* parameters using as the location of the onset and end of the QRS those locations relative to the fiducial point found on the control lying EKG.

Upon completion of the study the cardiologist may review the data which has been stored on the patient. If an erroneous code (identifying stage and time) had been transmitted with a set of data he may edit the code by changing it to the proper code for the final report. He may also delete from the final report any sets of data that he feels are redundant to the study. Having thus verified and edited the data, it is stored on a magnetic tape. These stored records will be used in the future to compare various diagnostic parameters for determination of that set of parameters which is most diagnostic in correlating with ischemic heart disease. These records will be compared against other clinical findings such as coronary arteriograms, in order to develop computer algorithms for automated interpretation of the record.

A three-part report is generated using a digital *X Y* plotter which is connected to the computer system. Part 1 is a plot of the representative averaged QRS complex from each of the three simultaneous leads with values for *ST* segment level and slope and heart rate, Part 2 is a plot of the heart rate response during exercise and the heart rate recovery toward normal following exercise. Part 3 is a plot of the time course of the *ST* segment level during the entire test. Figure 4 is a sample of the first part of the patient report as generated by the plotter. As

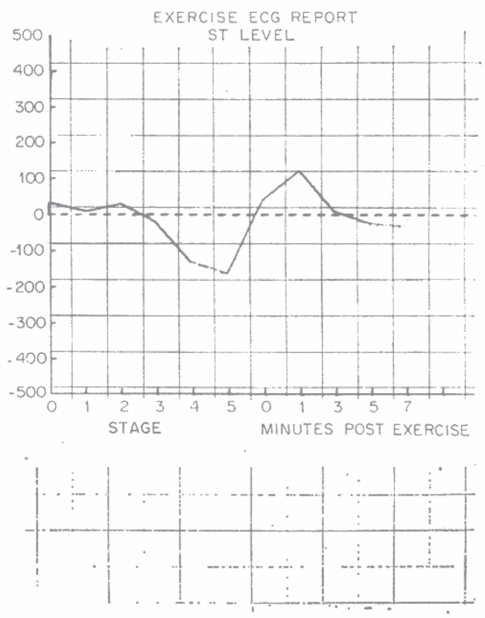

FIG. 6. Part 3 of the computer report showing the ST level of the monitoring lead during and after exercise.

seen in the figure, the left-hand column gives the stage of exercise followed by the graphs of the three simultaneous waveforms which were processed at that stage. The waveforms are calibrated such that one inch equals one millivolt and the time scale is .1 inch equals 50 milliseconds. The calibration pulse at the bottom of the figure is a one millivolt 100 millisecond pulse. Underneath the graph of each complex are written the magnitude of the ST level and the slope of the ST segment. The units of these parameters are microvolts and microvolts per second, respectively. Figure 5 shows the plot of the heart rate response to exercise. There are two graphs, the heart rate response to exercise in the upper half of the figure and the recovery heart rate in the lower half. The third part of the report is shown in Fig. 6, and consists of the plot of the ST segment level for the monitoring lead during the various stages of exercise and during the post-exercise phase of the study.

In giving his interpretation the cardiologist now has available to him the strip-chart recordings of the ‘‘raw” data and the averaged complexes as generated by the above report. He uses all of this information in finally determining the appropriate interpretation of the test.

The program has been in routine operation for approximately nine months at the Latter-day Saints Hospital with an average of six patients per week being given the test. Ease of interpretation of the test has been enhanced by use of the generated report. Of particular use has been the plot of ST segment level for the “monitoring lead”. Investigations are now going on to determine optimum leads for monitoring. As these leads are established correlation studies will be undertaken to identify optimum parameters to be measured.

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